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[illegible] ATMOSPHERIC [illegible] HAZARDS

[illegible] Research Institute

Bureau of Aeronautics
United States Navy
Washington, D. C.

and

Wright Air Development Division
Air Research & Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

WADD TN-60-35

AIRCRAFT PROTECTION
from
ATMOSPHERIC ELECTRICAL HAZARDS

Quarterly Report No. 11
Covering the Period
October 1959 through December 1959

Lightning & Transients Research Institute
Minneapolis, Minnesota
L&T Report 363
Contract No. AF 33(616)-3991

January, 1960

Project No. 7(77-4357)
Task No. 43387

Jointly Sponsored by

Bureau of Aeronautics
United States Navy
Washington, D. C.

and

Wright Air Development Division
Air Research & Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

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FOREWORD

This report was prepared by the Lightning and Transients Research Institute under Contract AF 33(616)-3991 sponsored jointly by the Wright Air Development Division, U.S. Air Force and the Navy Department, Bureau of Aeronautics.

The technical program is administered under the direction of the Communications and Navigation Laboratory, Wright Air Development Division, Mr. H. M. Bartman acting as project chief, and coordinated with the Navy Bureau of Aeronautics through Mr. V. V. Gunsolley.

Participating scientific and engineering staff taking primary part in this report's researches and preparation included: M. M. Newman, J. R. Stahmann, and J. D. Robb.

ABSTRACT

Recent studies have revealed the possibility that aircraft explosions could be caused by the ignition of the fuel vent vapors due to streamers resulting on the rim of the vent tube with a lightning stroke to any part of an aircraft; When an aircraft becomes part of the lightning channel, the aircraft potential rises to the order of 10^8 volts and the electrical gradient about the aircraft is large enough to initiate streamers off many points on the aircraft, including fuel vent tubes in relatively shielded locations. Preliminary measurements under a related NASA sponsored program have shown that such streamers have enough energy to ignite certain fuel vapor mixtures, and these do not leave tangible evidence of having occurred such as pit marks. Thus consideration should be given to a review of potential hazards at various specific fuel vent installations and to the development of protective measures such as vent shielding.

Interim lightning protection measures for nonrigid airships were also considered.

PUBLICATION REVIEW

Manuscript copy of this report has been reviewed and found to be satisfactory.

Lightning & Transients Research Institute

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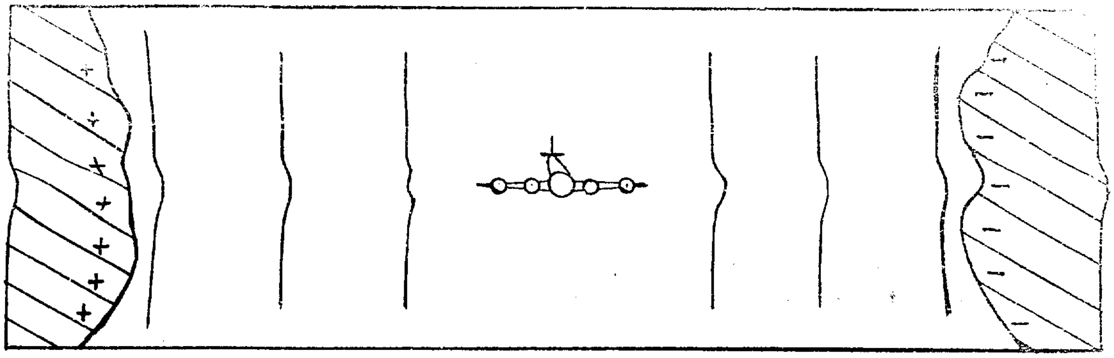
When an aircraft is contacted by a lightning discharge channel, its potential may be raised to the order of 10^8 volts in less than a microsecond. Under these conditions, streamers may be generated from almost any point on the aircraft including possibly hazardous fuel vent locations in relatively shielded locations. Initial investigation indicates that the currents of such streamers could ignite certain fuel vapor mixtures in the region of the vent tube possibly resulting in an aircraft explosion. While the probability of such an occurrence is undoubtedly small, immediate consideration should be given to a review of fuel vent installations with consideration of methods for reducing this hazard. Available statistics on lightning hazards can be misleading since direct evidence of lightning induced streamer caused aircraft explosions would be almost impossible to obtain and the lack of such evidence leads to overoptimistic conclusions.

A conference on a prototype system of lightning protection for a Navy airship was also held at our laboratory with Navy personnel during this period.

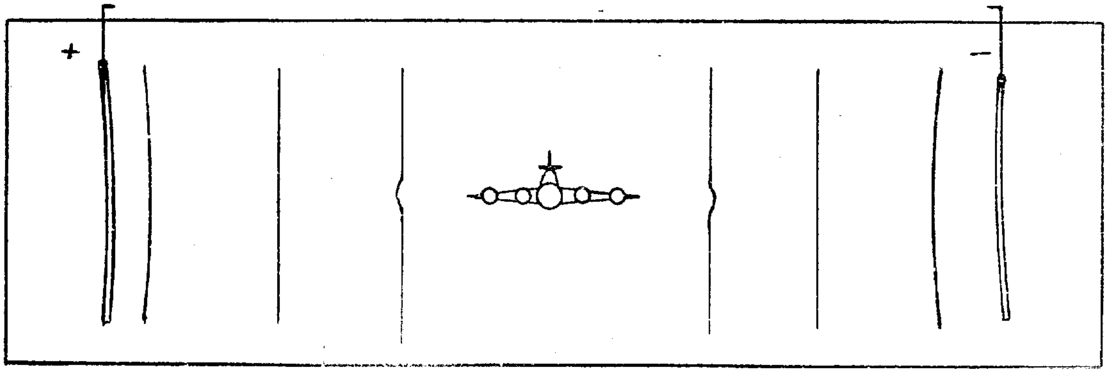
II. Lightning Induced Streamers from Simulated Vent Tube

An aircraft in a cloud-to-cloud field gradient, shown in Figure 1(a), was duplicated electrically in an electrolytic tank as shown schematically in Figure 1(b) with a photograph of the actual setup presented in Figure 1(c). With the electrolytic tank setup the changes in the gradient about the aircraft as a lightning stroke (represented by a wire in the tank) approaches, contacts and passes through the aircraft are shown in step by step fashion in Figure 2. From this figure it can be seen that the gradient near the aircraft increases very rapidly in the time it takes the channel to progress a distance equal to about a wingspan. Considering the velocity of the channel as nearly c/10, where c is the speed of light, we obtain a channel velocity of 30 meters per microsecond producing a sudden gradient increase about the aircraft in less than a microsecond. Thus, the aircraft would suddenly rise in potential about 10^8 volts producing gradients such as those shown in Figure 3(a), in percent of aircraft voltage. The field gradients about the aircraft are high enough to produce streamers from almost any point including the fuel vent tubes as shown in Figure 3(a) even if they are partly shielded by the aircraft structure. A detail of a gradient plot about a simulated vent tube is shown in Figure 3(b). The gradient at the end of the vent tube is high enough to initiate streamers into a region which may contain an inflammable fuel mixture.

To simulate fuel vent streamers in the laboratory we used our 7 million volt impulse generator to produce an impulse field above a



(a). Aircraft in gradient between clouds.



(b). Gradient simulated in electrolytic tank.

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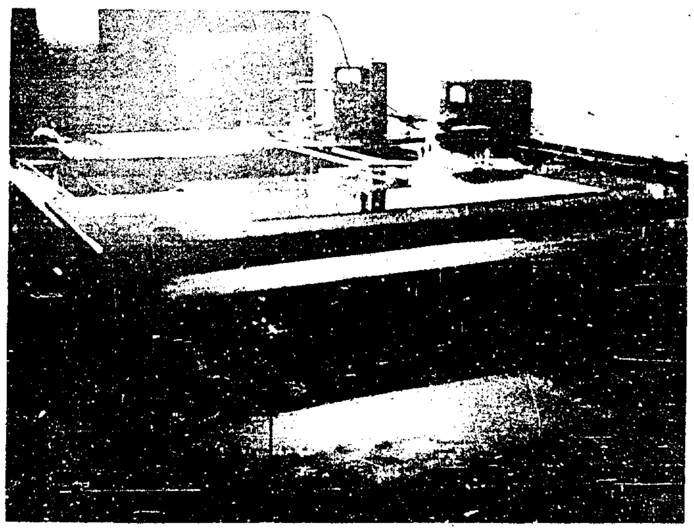


(c). Electrolytic tank setup.

Figure 1. Electrolytic tank simulation of aircraft in cloud-to-cloud field.

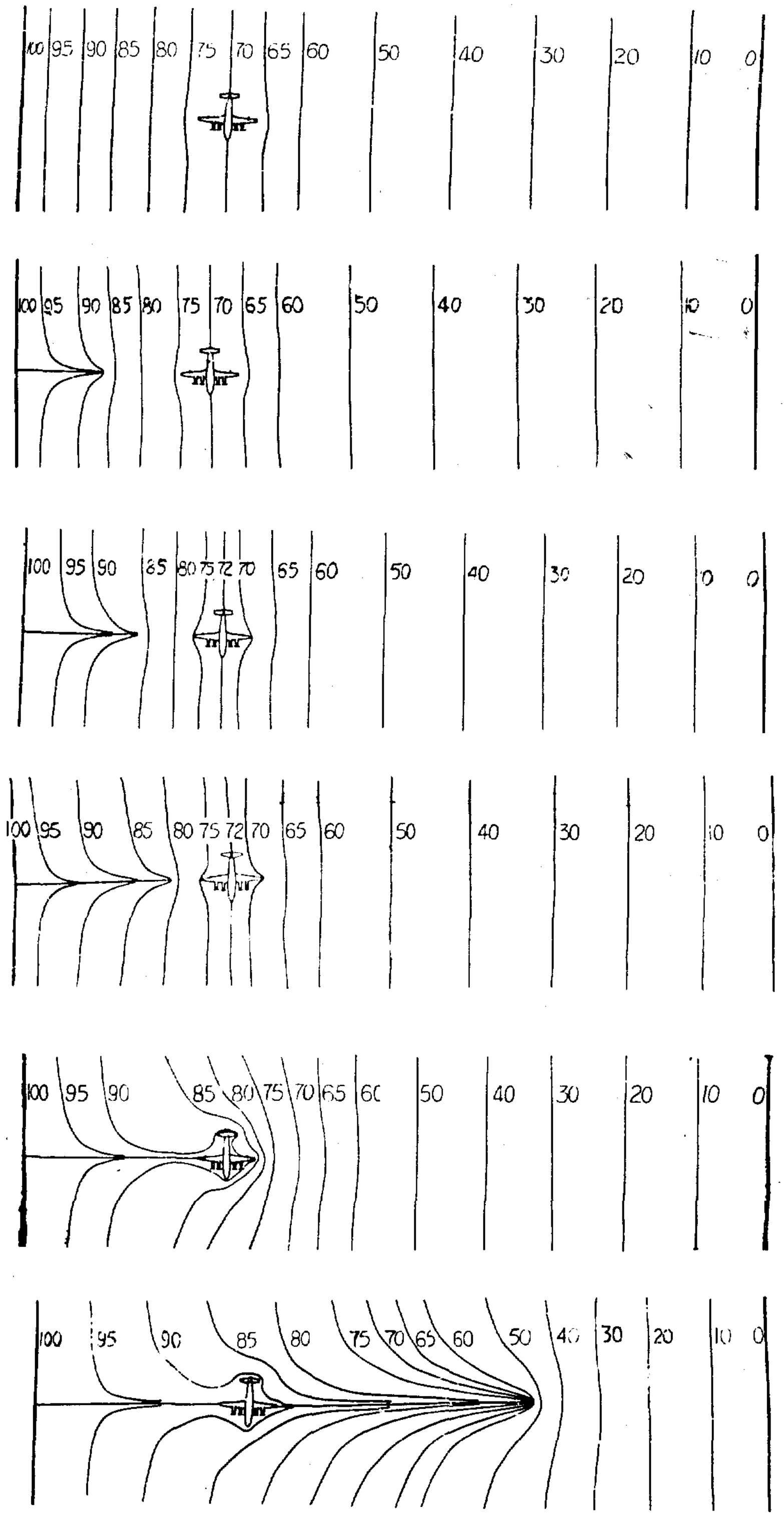
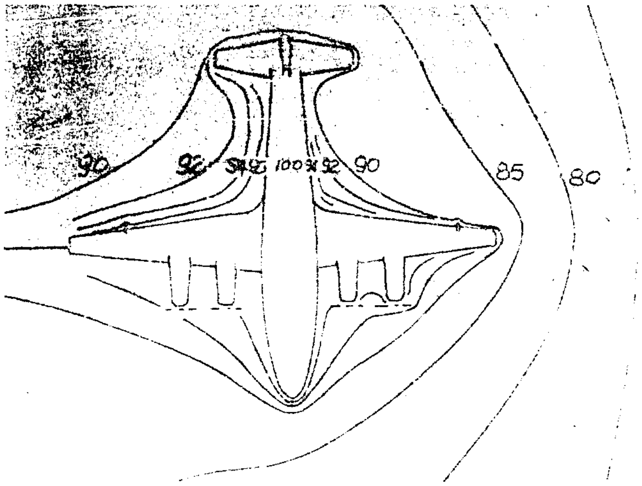


Figure 2. Gradients of different stages of lightning discharge through aircraft.



(a). Gradient about aircraft.

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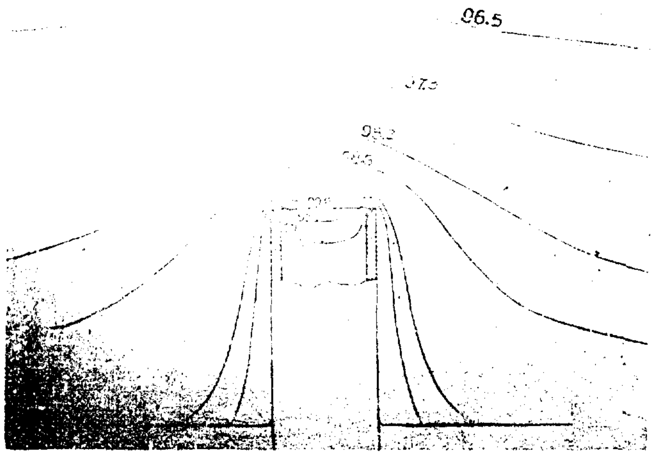

(b). Gradient about simulated vent tube.

<u>Figure 3.</u> Gradient plots about aircraft and vent tube.

cylindrical simulated vent tube about 4 inches in diameter. The vent tube was placed on the test floor and connected to ground through a 10 ohm current measuring shunt as shown in Figure 4. The voltage output of the shunt was measured by an oscillogram connected to the shunt by means of a terminated RG-8/U cable. A large cylinder was connected to the impulse generator and placed about 8.5 feet above the vent tube, as shown in the figure, to simulate a cloud. At the spacings used, the voltage of the impulse generator could be raised to about 2.5 million volts without arcing across the gap. Under these conditions streamers such as those shown at the right in Figure 5 were produced. Oscillograms taken simultaneously with the photographs of each streamer group are shown at the left. Peak currents ranged from about 20 to 120 amperes with durations of one to two microseconds. The double hump in the waveforms shown in Figure 5(b) and (c) does not have special significance since it was probably due to a slight oscillation in the generator voltage wave. Individual streamer currents were of the order of 10% of the peak composite current since the number of visible streamers averaged about ten. This was confirmed by placing a wire just inside the rim of the vent tube and connecting it at the shunt. The tube itself was grounded. Peak currents of from 10 to 30 amperes were obtained for these single streamers. Single streamer oscillograms and correlated photographs are shown in Figure 6(a) and (b). In each photograph the longest streamer is that which corresponds to the oscillogram. Fine structure or high frequency components, which would correspond to branching streamers, are only slightly evident in the oscillograms and hence represent relatively small currents.

As discussed in Appendix I, peak currents of the order of one ampere and pulse durations of about one microsecond would be required to ignite fuel vapors. As shown in Figure 7, a pulse having a peak current of 10 amperes and a duration of about 0.5 μsec, corresponding to the waveform shown in Figure 6(a), could cause ignition. This point is marked "x" on the plot and lies just above the extrapolated (dashed) curve. A point corresponding to some typical streamers is marked "o" above the curve and corresponds to the waveform shown in Figure 6(b) which has a peak current of 16 amperes and a duration of about two microseconds.

In the case of DC corona, currents as low as 200 μamps from a single resistive point will ignite fuel vapor. In contrast to the high current streamers caused by high lightning field gradients, it is questionable whether sufficient corona currents would or would not result from precipitation-static charging to be a hazard in existing fuel vent installations. However, to check on precipitation-static phases some tests were started using our DC generator setup as illustrated in Figure 8(a). A simulated fuel vent was installed on top of the LTRI DC generator as illustrated in the figure with a microammeter connected to the vent for monitoring the corona current.

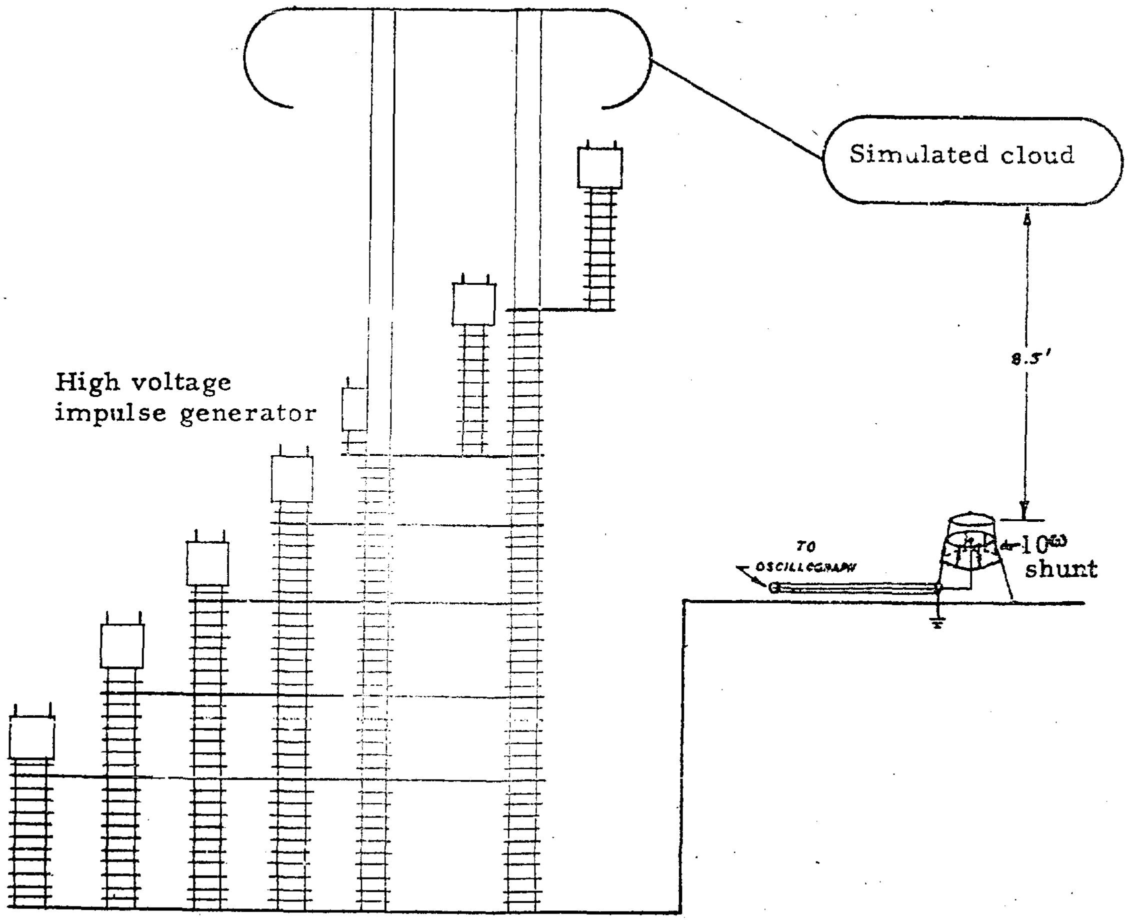

Figure 4. Laboratory test setup for simulated vent tube streamer measurements.

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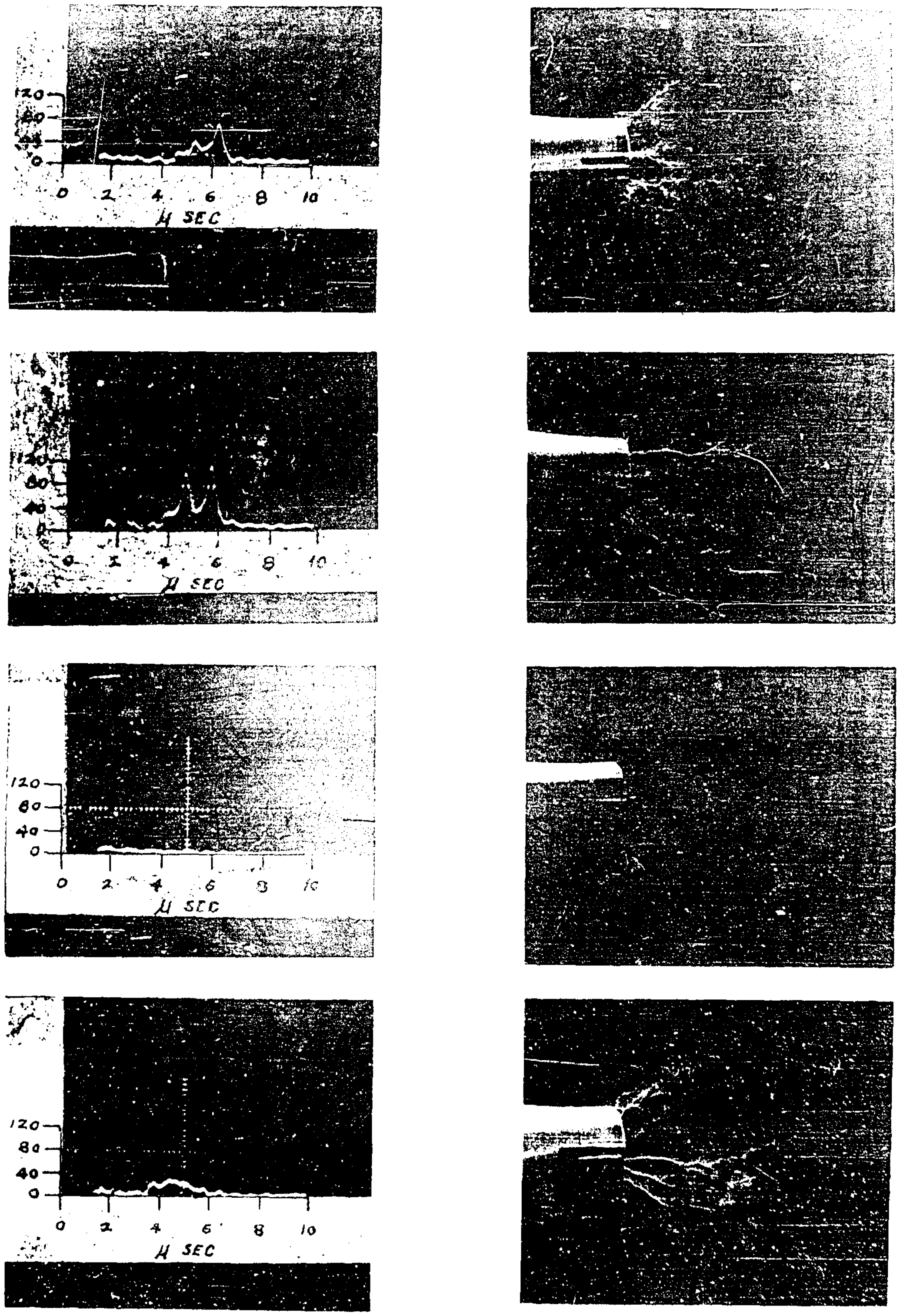

Figure 5. Correlated oscillograms and photographs of simulated vent tube streamers.

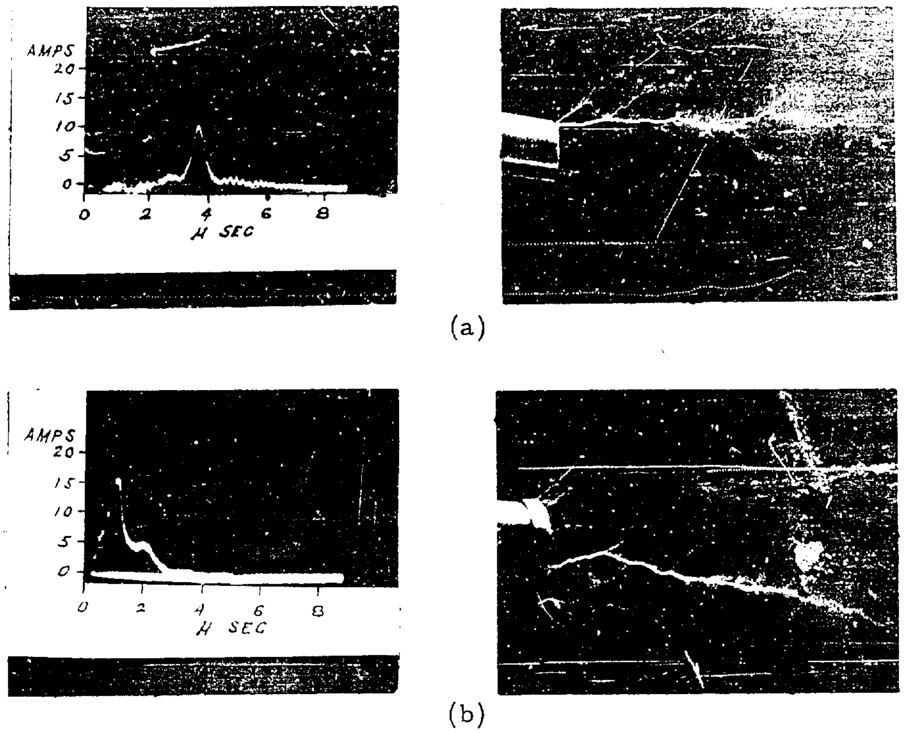

Figure 6. Current waveforms and photographs of single streamers.

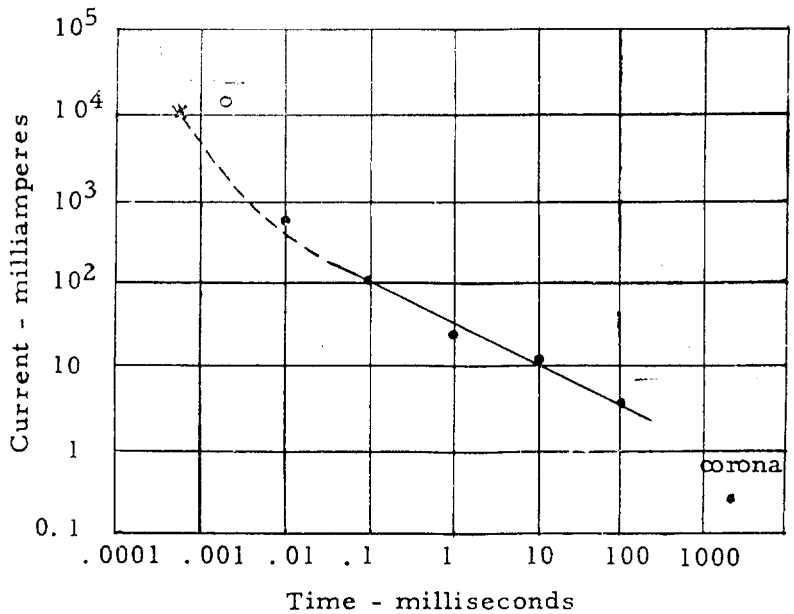

Figure 7. Plot of minimum current vs. time duration for capacitor discharge ignition of aviation gasoline 100/130 grade.

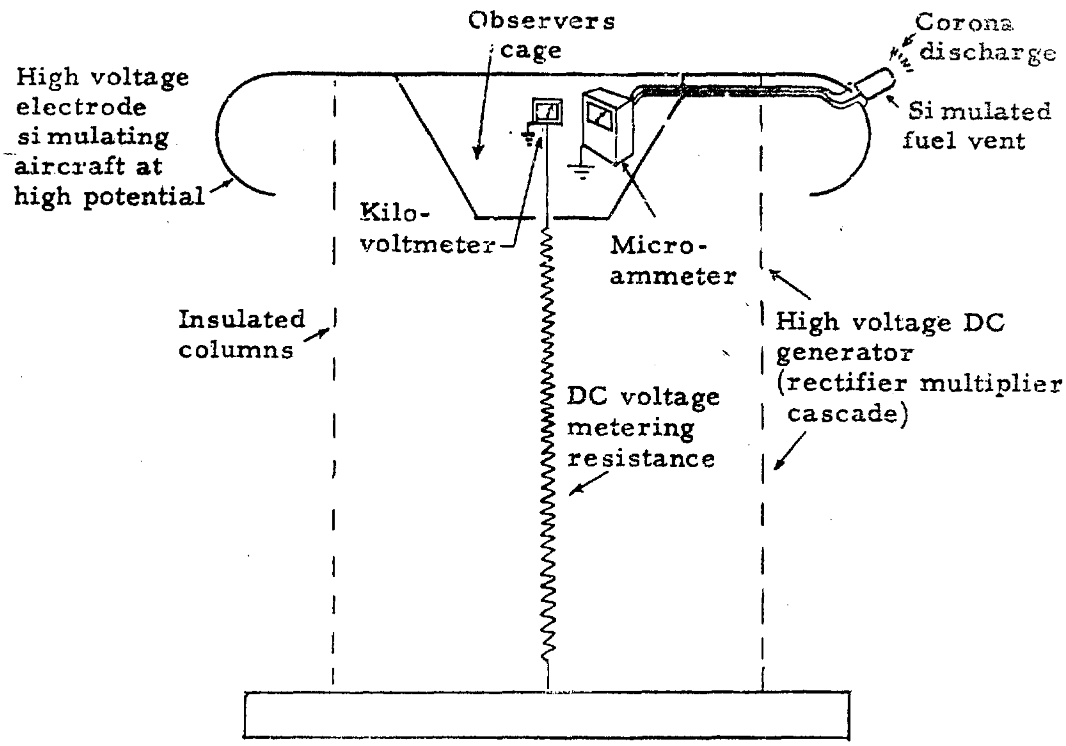

Figure 8(a). Diagram of test arrangement for measurement of corona currents off simulated vent tube.

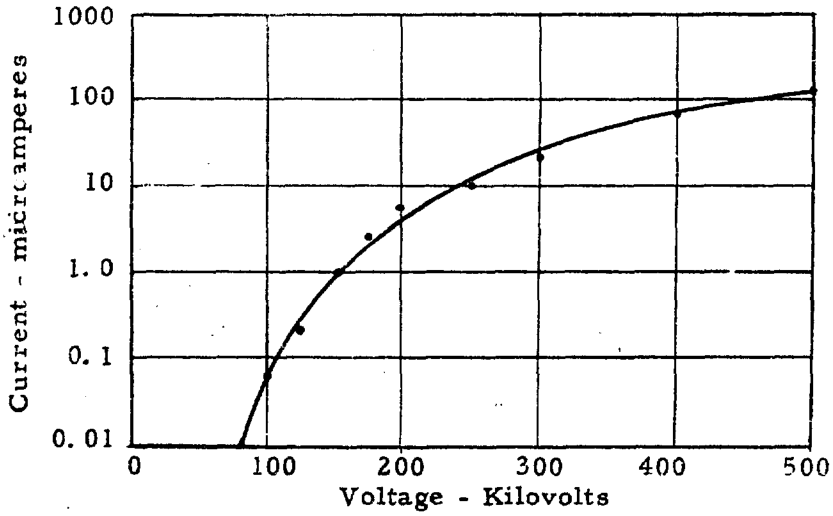

Figure 8(b). Graph of corona current vs voltage on vent.

The measured current on this particular vent, as presented in Figure 8(b), was found to be about 130 μamps at 500 kilovolts, a much larger potential than would normally result from aircraft friction charging. Airflow past the vent would increase the current by removal of space charge, but the amount of increase would have to be determined by wind tunnel tests.

III. Interim Airship Lightning Protection

A conference with Navy personnel on an interim lightning protection system for a Navy airship was held at LTRI on November 19, 1959, during the period of this report. In addition to a separate program for general lightning protection studies of nonrigid airships which has been proposed, as detailed in the previous quarterly report, Navy Bu Aer plans to go ahead with an interim system. At the LTRI conference the following subjects were among the points discussed:

1. Heat resistant flexible materials for insulating the aluminum or copper diverter strips from the fabric envelope of the ship. These strips would be placed along the top and bottom of the airship and perhaps along the sides.

2. Electrical and mechanical forces on the strips and the effects of vaporization due to heating at the arc contact points.

3. A folding combination antenna-diverter for radome lightning protection.

4. Lightning protection of power cables in the mooring mast by shielding and using lightning arresters.

5. Grounding of the mooring mast and the possibility of adding a counterpoise system.

6. Adequacy of bonding.

7. Diverter locations and orientations.

8. Current distribution in airships.

9. Radome lightning hazards.

10. Lightning hazards to airship power system.

Most of the above points will require considerable work beyond the scope of the presently authorized program. However, within the present

state of the art, some checking tests are planned to incorporate as many improvements as are practical in the interim fix.

In a preliminary study of the lightning protection of an airship, a model of the airship was placed in the field of our impulse generator and the locations of the arc contact points on simulated protection strips with and without a diverter were determined.

A typical simulated lightning discharge to the airship is shown in Figure 9 including streamers which could have connected with the main channel to produce branch channels along the under side of the model. Such branching is illustrated in Figures 10(b) and 11(a). Figures 10(a) and (b) show horizontal and vertical strokes respectively to the airship with protective strips along the top, bottom, and both sides of the airship. When a diverter rod was placed above the ruddervator tab of the model, the results are shown in Figures 11(a) and (b). From these studies it is evident that it is difficult to determine the effects of a diverter on the ruddervator of a small scale model because of the relative size of the arc channel. Either a larger model or a mockup of the ruddervator on a larger scale will be required for further diverter studies on this section of the airship.

IV. Concluding Discussion

Initial investigation indicates that lightning induced streamers off aircraft vent tubes could ignite fuel vapor mixtures in the region of the vent tube, possibly causing an aircraft explosion. Such streamers would be produced even in areas shielded by the aircraft structure when any part of the aircraft is contacted by a lightning channel since the aircraft potential rises very rapidly to about 10^8 volts. Since past work has shown that streamers probably do not leave any tangible evidence of occurrence, such as pit marks, it is difficult to prove that a specific explosion was caused by this mechanism. However, present report studies indicate that, while the probability of such an explosion may be small, consideration should be given to a review of fuel vent installations. Flame arresters, which will not introduce other hazards such as icing, should be developed and installed where possible or the fuel vents should be shielded electrically from streamers by specifically developed fuel vent shielding.

As part of our general studies of lightning and associated precip-static reduction techniques on such vehicles as jet bombers and fighters, missiles, helicopters, and airships, a consultation with Navy Bu Aer on an interim lightning protection system for nonrigid airships has been started and will continue under this program. The airship diverter techniques studied and developed are applicable to other vehicles such as those above.

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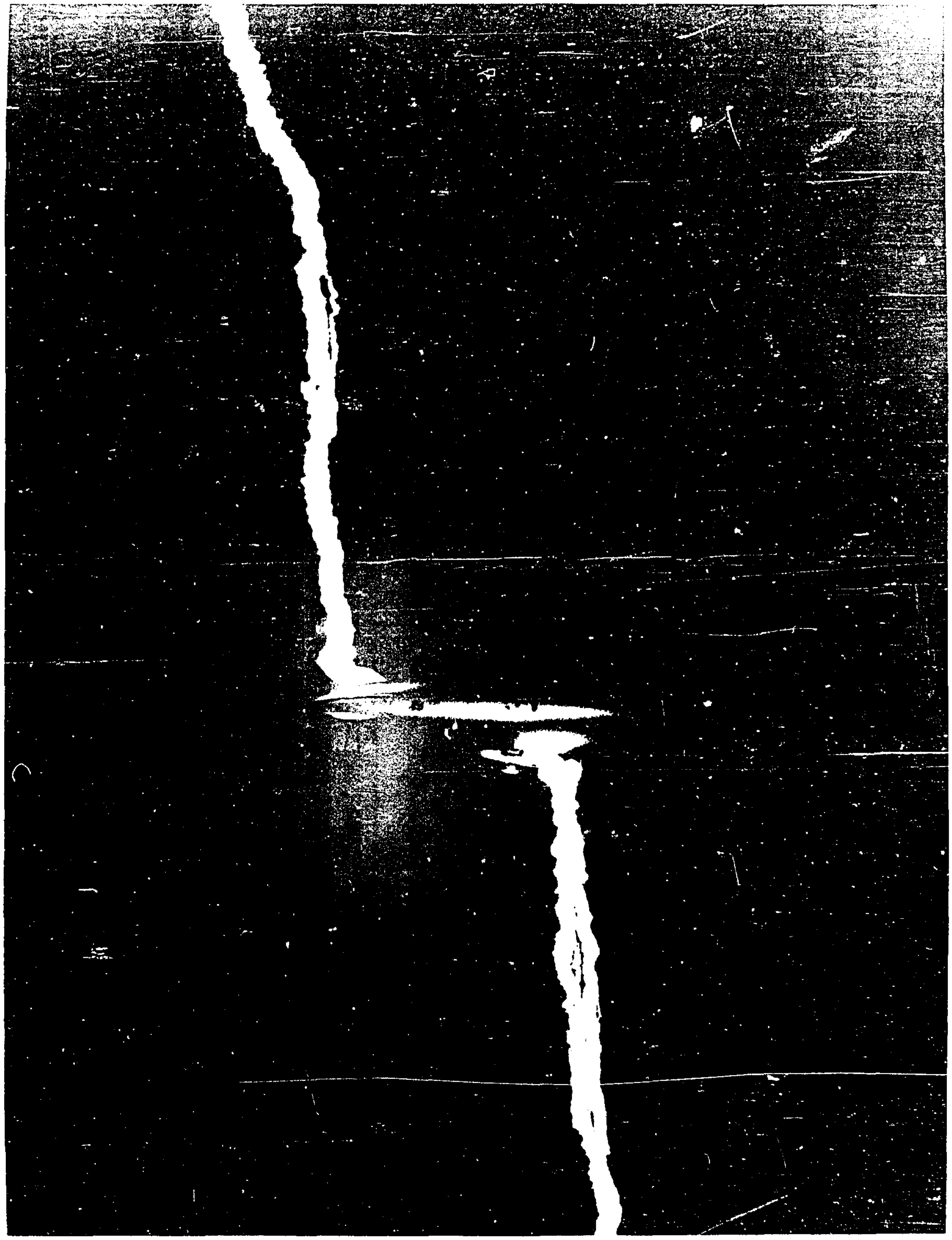
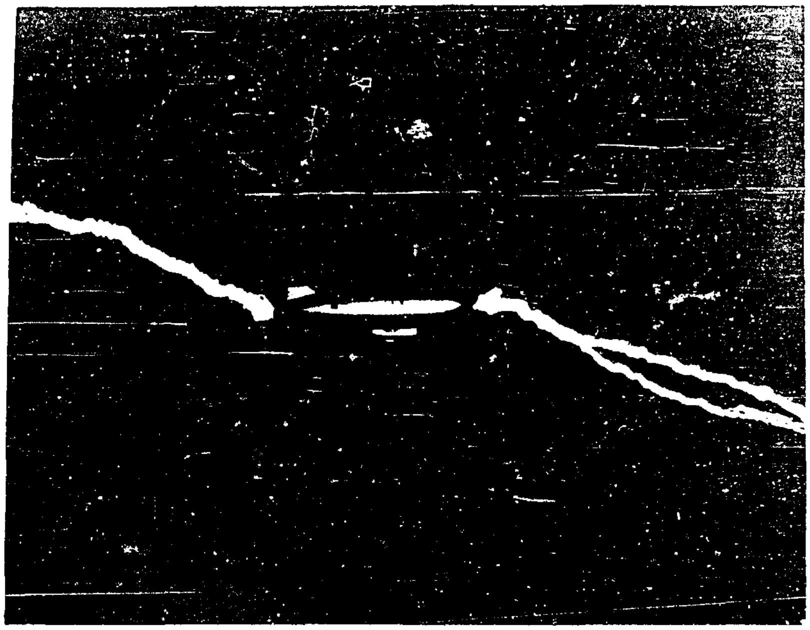


Figure 9. Simulated lightning discharge to an airship with protective strips.



(a)

(b)

Figure 10. Horizontally and vertically oriented simulated lightning discharges with protective strips on airship model.

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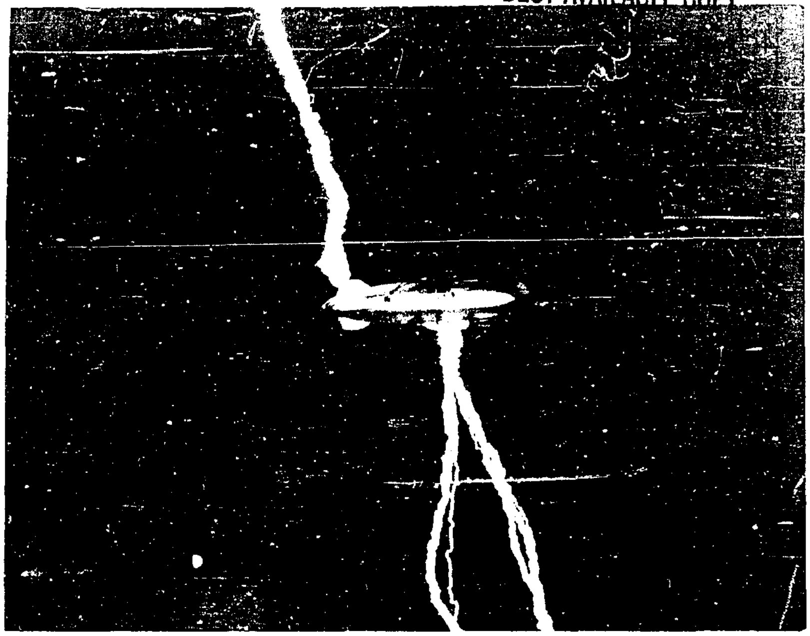

(a)

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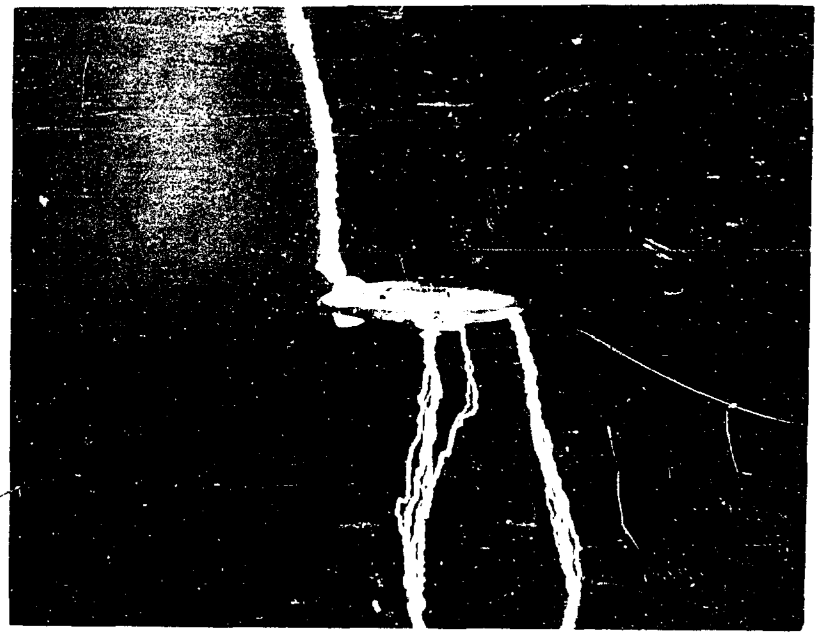

(b)

Figure 11. Simulated lightning discharges to ruddervator with simulated diverter rod above ruddervator tab.

Appendix I, Report No. 363 December, 1959

Excerpt from

LIGHTNING HAZARDS TO AIRCRAFT FUEL TANKS
Part II - Corona Discharge Ignition of Fuel Vapors

Final Report, Part II
Jan. 1958 - Sept. 1959

NASA Contract
No. NAw-6535

III. Studies of Minimum Spark Ignition Currents and Time Durations

Lightning discharges to an all-metal aircraft, although effectively shielded from the interior by the all-metal skin, can induce voltages on conductors such as the control cables, navigation light wiring, de-icing heater wires, etc., which pass through the skin into the aircraft interior and studies have been made to determine the possibility of such potentials igniting fuel vapors. As induced potentials are related to current rates of change rather than magnitudes, they are expected to be of short duration corresponding to the steep current wave fronts on some type of lightning discharges, typically cloud to ground strokes, and therefore, current magnitudes versus time durations required to ignite fuel vapors were determined in these studies. Aviation gasoline was used for a fuel, for although it is less easy to obtain a known concentration than with gaseous fuels such as methane or ethane, the results are more directly applicable to the problem of fuel ignition in aircraft.

Earlier investigators have been concerned primarily with the energies required for ignition and considerable data exists on this subject, but for discharges described as capacitive or inductive, rather than in terms of current wave-shapes possible with modern oscillographic techniques. For correlation with earlier investigations, some tests were made to determine the minimum energies using the test arrangement shown in Figure 3. Measured amounts of aviation gasoline were placed inside a quart container which had a spark gap located near the bottom. A variable condenser was adjusted to a given capacity using a Boonton Q meter for calibration. The Q meter was then disconnected after correction for meter lead capacities and the capacitor was charged to a given voltage after which it was discharged to the spark gap inside the fuel cell. The spark gap in the fuel cell consisted of two ball gaps spaced up to about 1/8 inch. For a given setting of the variable capacitor the charging voltage was lowered after each test until ignition no longer occurred and the minimum voltage for a given capacitor setting was recorded. After each test the fuel cell was aired to remove combustion products from the previous test, a new charge of fuel was placed inside the cell and the fresh fuel was allowed 15 to 45 seconds for evaporation before beginning the new test.

Using this test arrangement the values of minimum charge voltage for a given capacity were obtained and these values are presented in the graph of Figure 4. As may be observed on the graph, the charging voltages varied from 16,000 volts for approximately 5 micromicrofarads to less than 7 kilovolts for 36 micromicrofarads or, in terms of energy, $1/2\ CE^2$ from 0.64 to 0.88 millijoule.

The amount of fuel added to the fuel cell was approximately that required for a stoichiometric mixture and this value was arrived at by calculation and by experimental tests to determine maximum explosion pressures.

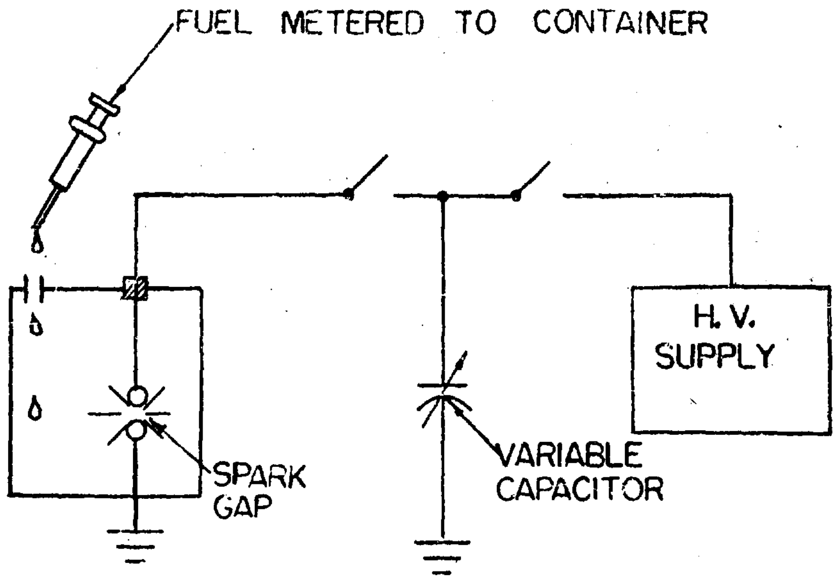

Figure 3. Test arrangement for determining minimum capacity vs. voltage required for spark ignition of aviation gasoline.

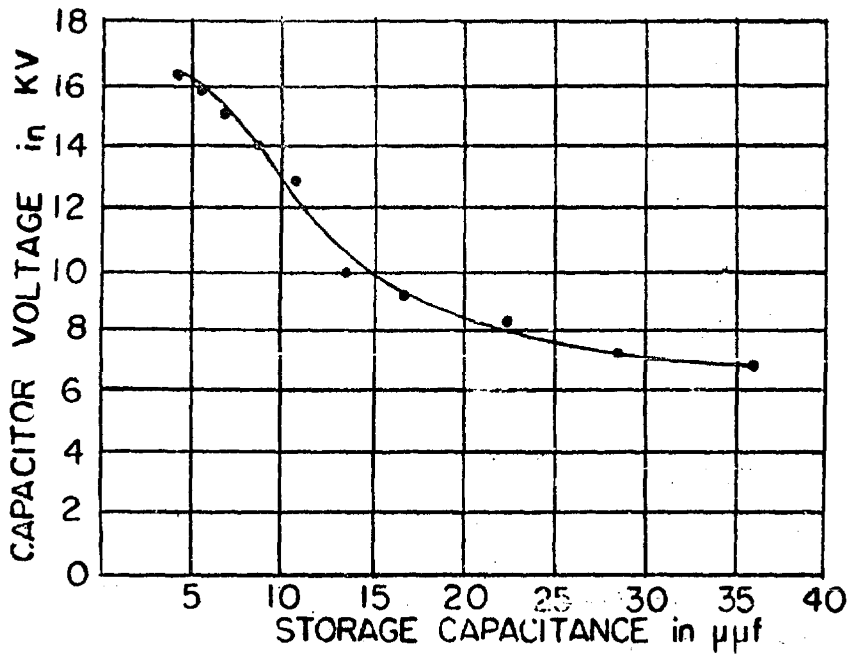

Figure 4. Curve of minimum capacity vs. voltage required for spark ignition of aviation gasoline.

The preceding work is in agreement with other investigators' findings that energies of the order of a millijoule concentrated in a short spark will ignite flammable fuel vapors. To relate the data to discharge transients dissipating only a portion of their energies in the flammable area, other measurable criteria than source energies must be used. Consequently a series of tests were devised relating fuel vapor ignition to current and time variations.

The test arrangement for the study of spark ignition current-time variation is shown in Figure 5. Measured amounts of aviation gasoline were placed in a quart container and after 30 to 45 seconds allowed for evaporation of the fuel, the mixture was ignited by a spark gap near the bottom of the container. The spark gap consisted of two 3 mil needle points spaced 1/16 inch apart, one grounded at the bottom of the container and one connected to the high voltage lead. The high voltage lead was connected through a control resistor to the storage capacitor and by selection of storage capacity, resistor magnitude, and charge voltage, discharges of various magnitudes and time durations could be obtained. The container was grounded through a current measuring resistance across which was connected the oscilloscope for monitoring of current waveshapes. The resistance was limited to about 1000 ohms to limit capacity errors possible with the high frequency discharge components. The discharges were essentially typical capacitor discharges with exponential current decay modified slightly by the nonlinear spark resistance and the stray spark gap capacity. Typical oscillograms replotted to equal scales for comparison are presented in Figure 6. The results of the fuel ignition tests are presented in the graph of Figure 7.

The time durations presented in the graph of Figure 7 are the times "t" required for current decay to about one-third value and the currents shown are peak current values "I max" of the fundamental discharge waveshape. The solid line drawn approximately corresponding to the experimentally measured points gives an interesting criterion of "$I^2_{max}t$" being a constant which would correspond to a constant minimum ignition energy in the spark, if the spark resistance were constant. However, the spark resistance varies and would tend to be higher for the shorter time duration discharge providing higher energies which are apparently balanced by the lower effectiveness to be naturally expected of shorter duration sparks in producing ignition. A point corresponding to the value for an average corona current discharge, discussed in the previous section, is indicated in the lower right of the graph for comparison.

As may be seen in the graph of Figure 7, ignition currents of over one ampere would be required for very short discharges of about 1 microsecond; whereas, for continuous average corona currents, only about 200 microamperes are required. The above information, as pointed out previously, is important in evaluating hazards from possible high gradient induced corona and streamers near fuel vents and also from possible internal inductive voltage drop sparking which might ignite possible fuel leak vapors inside the aircraft.

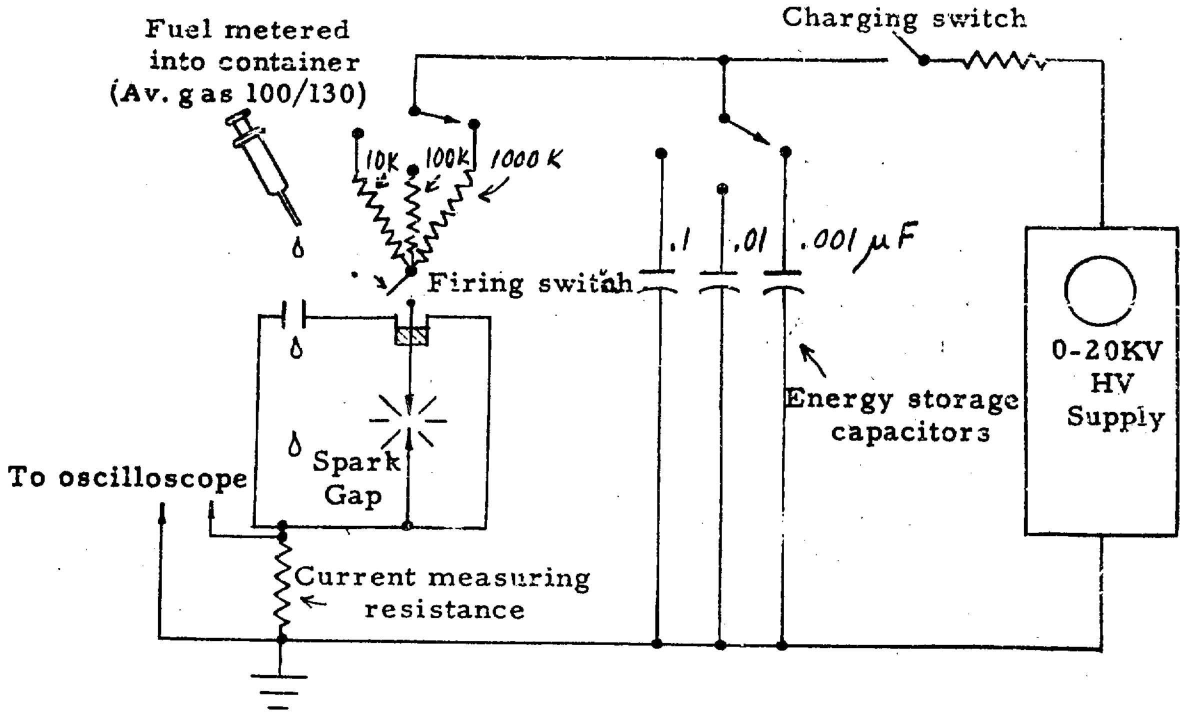

Figure 5. Test arrangement for measurement of current amplitude and time duration required for fuel vapor ignition.

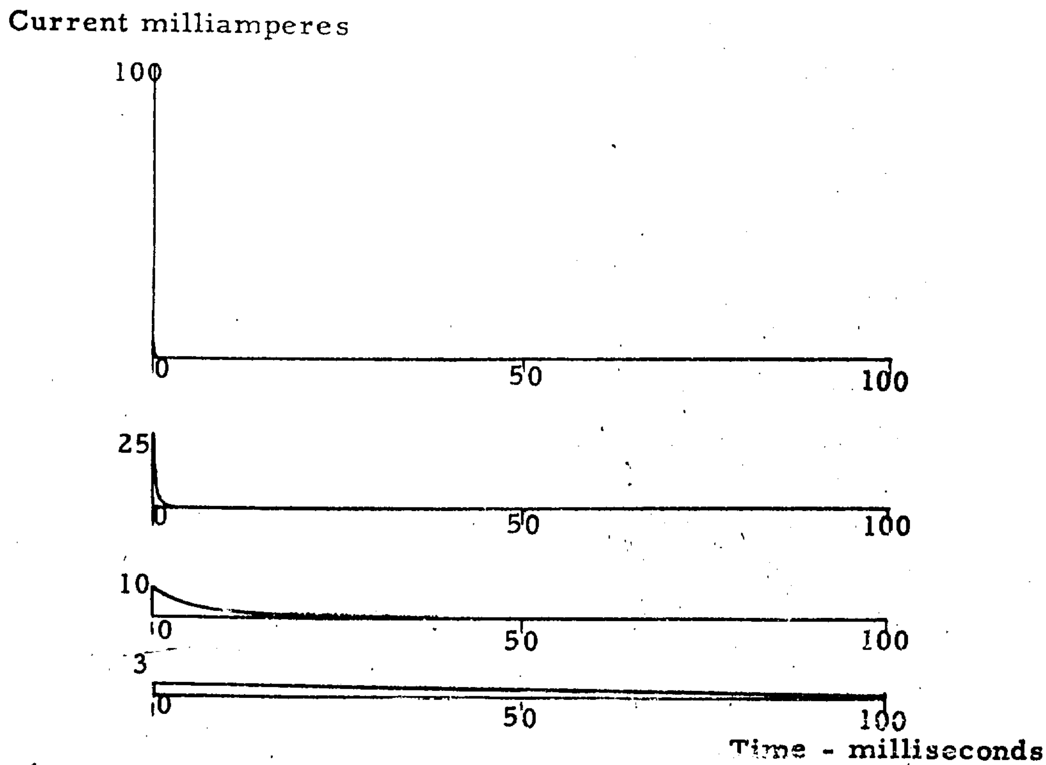

Figure 6. Typical current wave shape oscillograms recorded, replotted above to equal scales, equally capable of fuel vapor ignition.

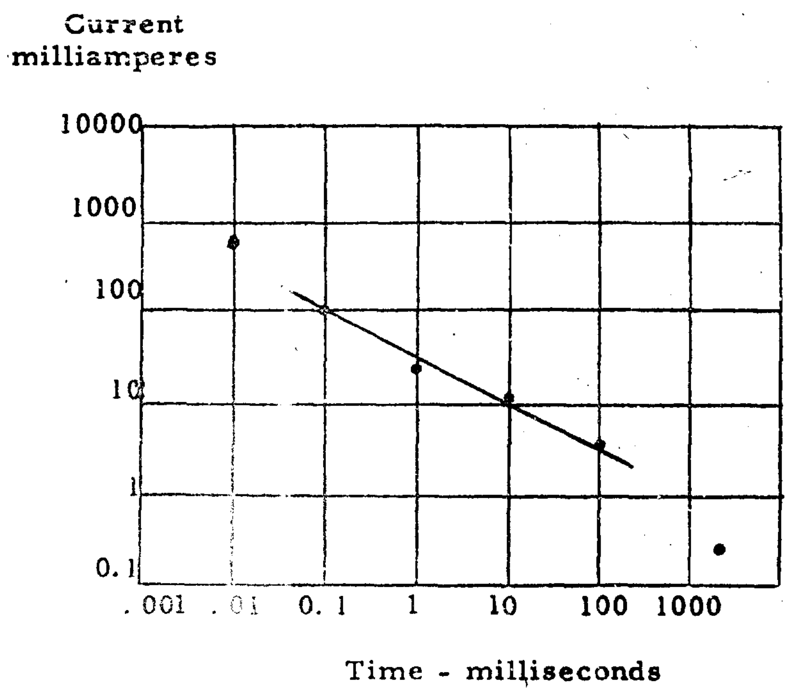

Figure 7. Plot of minimum current vs. time duration for capacitor discharge ignition of aviation gasoline 100/130 grade.